

1/PRTS

Abstract

For many human body motion analysis, diagnosis, or surgical operations, it is previously required to accurately determine the position of the center of a femoral head with respect to a referential linked to a patient's femur or pelvis. It should be noted that this determination in itself is not a diagnosis operation, nor a medical or surgical operation. It has no effect on the considered organ and may be performed on a healthy organ, to analyze its motion and, for example, foresee the athletic capacities of an individual. Further, even if it is used with a view to diagnosis or with a medical or surgical aim, it is only an accessory thereof, in the same way as a doctor

needs to know the size and weight of a patient as diagnosis elements.

5 A method for determining the center of rotation of a femur with respect to the pelvis is for example described in international patent application WO-98/40037 published on September 17, 1998, and assigned to Aesculap Company.

10 This patent application provides, to determine the center of rotation of a femur with respect to a pelvis, use of several markers provided with light-emitting diodes driven into bones of the patient. The markers are associated with known systems of localization by triangulation. A first marker is fastened in the femur and a second marker is fastened in the iliac bone. The femur is moved according to several positions. Each of the positions of the first marker is detected by using a
15 triangulation system and is stored in a calculator, taking into account the displacement of the marker fastened in the iliac bone. The invariant distance between the marker linked to the femur and the center of rotation of the femoral head can then be searched by various conventional mathematical minimization
20 methods using for example least error squares algorithms.

This system has provided full satisfaction, but it has the disadvantage of requiring implantation of rigid objects into the femur and the iliac bone and thus provision of incisions.

25 The present invention aims at avoiding at least the implantation in the iliac bone.

To achieve this object, the present invention provides a method for determining the center of rotation of a bone in a revolute joint, including the steps of displacing said bone, locating several ones of its positions, and memorizing them;
30 imposing a constraint to the displacement of said center of rotation without for all this immobilizing it; and searching a point linked to the referential of said bone for which an optimization criterion taking into account said constraint is reached.

35 According to an embodiment of the present invention, applied to the determination of the center of rotation of a first

femur with respect to the iliac bone, the method includes the steps of immobilizing the second femur, displacing the first femur and locating several ones of its positions, and searching the invariants of this displacement, taking into account the fact
5 that the center of rotations of the first and second femurs are distant by a substantially constant length.

According to an embodiment of the present invention, the method further includes the step of locating upon each measurement of the position of the first femur the position of the
10 second femur to accordingly correct the position of the center of rotation between the first femur and the iliac bone.

According to an embodiment of the present invention, applied to determining the center of rotation of a first femur with respect to the iliac bone, the method includes the steps of
15 displacing the thigh so that said center of rotation moves along a trajectory which is clearly mathematically distinct from all other points of the lower femur portion, and searching this point having a specific trajectory by an optimization method.

According to an embodiment of the present invention,
20 the thigh is moved so that the knee follows a loop trajectory, whereby only the trajectory of the center of rotation will optimize a distance in the expression of which the number of loops and some of their mathematical characteristics will be involved.

According to an embodiment of the present invention, the thigh motion can be decomposed in several elementary motions, for each elementary motion, an optimal center of rotation and an optimized distance value are calculated, and the center of rotation is statistically defined, taking into account each of
25 the estimations of the center of rotation and of the optimized distance value, obtained based on each of the elementary motions.
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According to an embodiment of the present invention, applied to determining the center of rotation of a first femur with respect to the iliac bone, the method includes the steps of
35 moving the thigh so that its lower portion describes as simple a

trajectory as possible, including, in particular, no loops, so that the searched center of rotation describes a mathematically simple trajectory, and searching this point with a mathematically simple trajectory by an optimization method.

5 According to an embodiment of the present invention,
the thigh motion can be decomposed in several elementary motions,
for each elementary motion, an optimal center of rotation and the
value of the optimized distance are calculated, and the center of
rotation is statistically defined, by taking into account each of
10 the estimations of the center of rotation and of the value of the
optimized distance, obtained based on each of the elementary
motions.

According to an embodiment of the present invention, applied to determining the center of rotation of a first femur with respect to the iliac bone, the method includes the steps of performing a succession of elementary motions of the thigh, for each of these motions, searching the position of the center of rotation of the femur, assuming that said femur has remained fixed, and determining a confidence ellipsoid within which the probability of presence of the femur center of rotation is high, and calculating based on the confidence ellipsoids the position of maximum probability of the femur center of rotation.

According to an embodiment of the present invention,
some of the elementary motions of the thigh are performed in a
25 plane and are of small amplitude.

According to an embodiment of the present invention, some of the elementary motions of the thigh are performed by rotating the femur around its own axis.

The present invention also provides a device for determining the center of rotation of a femur with respect to the iliac bone, including means for locating several positions of the femur during motions thereof, means for imposing a constraint to the motion of said center of rotation without for all this immobilizing it, and calculation means for searching a point

linked to the referential of said femur for which a minimization criterion is reached, taking said constraint into account.

The foregoing objects, features and advantages of the present invention will be discussed in detail in the following non-limiting description of specific embodiments in connection with the accompanying drawing, which very schematically shows a lower portion of the person's skeleton.

More specifically, the single drawing shows iliac bone 1 and its right 2 and left 3 acetabuli (it should be noted that the right acetabulum appears on the left-hand side of the drawing, which is a front view) in which are engaged heads 4 and 5 of right and left femurs 6 and 7. The starting of tibias 8 and 9 and kneecaps 10 and 11 have also been shown.

A simple way of determining the center of rotation of a femur, that is, substantially the center of femoral head, would consist, as indicated in the above-mentioned patent application, of measuring several successive positions of the femur while the pelvis, and more specifically the iliac bone, are immobilized. A vector having an invariant top can thus be determined and the end of this vector indicates the center of rotation.

The locating of the femur position may be performed in various ways. In particular, systems for locating the position of transmitters - such as optical or infrared transmitters, but which could also be transmitters radiating at other wavelength or magnetic transmitters - which use sets of sensors and determine the position of each of the transmitters by triangulation, are known. An example of such an installation applied to the determination of the head position is described in the article of Innovation et Technologie en Biologie et Médecine (ITBM) journal, volume 13, N°4, 1992, by L. Adams et al., pages 410-424. There also exist systems sold under trade name "Optotrak" by Northern Digital Company.

Unfortunately, such a simple system poorly operates since it is very difficult to immobilize the pelvis of a patient laying on his back and, when his leg is moved, especially due to

the elasticity of the skin and muscles between the iliac bone and the table on which the patient lies, the pelvis is inevitably moved. Thus, as described in the preceding patent application, a second localization system or marker inserted in the iliac bone has to be used. This requires performing an incision into the skin and piercing the iliac bone to fixedly position a marker therein. The present invention essentially aims at suppressing this step.

The present invention provides a system that avoids implantation of a marker into the iliac bone and which does not require perfect pelvis immobilization. Generally, the present invention provides imposing constraints to the pelvis motions by various physical processes and deducing from these physical constraints mathematical characteristics of the trajectory of the center of rotation enabling identification thereof.

In a first embodiment the present invention is based on the two following observations. The first observation is that, if it is very difficult to immobilize the pelvis of a patient lying on his back, it is however possible to immobilize his thigh, and thus his femur, by mechanical, pneumatic or vacuum systems, which compress and block the thigh or knee. The second observation is that, given the structure of the human body, it is possible to fasten an external marker against the femoral condyles, the position of this marker remaining perfectly fixed with respect to the femur.

In this first embodiment of the present invention, to measure the position of the center of a femur head, for example left femur head 5, the present invention provides attaching the patient's opposite thigh, containing femur 6. Thus, right femur head 4 remains fixed. The only possible motions of the iliac bone then are rotation motions around this femur head. Designating by C the center of rotation of head 5 of femur 7 and by D the center of rotation of head 4 of femur 6, since point D is fixed, point C can only move on a sphere centered on point D. Thus, a point O attached to femur 7 can only move according to a combination of

motions including a rotation of fixed radius around point C, and a rotation of fixed radius of point C around point D.

Knowing several positions of point O and the corresponding femur orientations, the problem to be solved to determine the position of point C is an optimization problem. Various methods for solving this problem may be used: general non-linear least error squares methods, methods adapted to cases where the expression to be minimized is a square of sums of squares, formal calculation methods for solving polynomial equation systems...

Descriptions of these and other methods can be found in the following works:

NAG program library, Numerical Algorithms Group ldt,
Wilkinson House, Jordan Hill road, Oxford, UK OX2 8DR,

15 IMSL program library, International Mathematical and
Statistical Library, Visual Numerics inc., 9990 Richmond Suite
4000, Houston, TX 77042, USA,

Régression non linéaire et applications, A. Antoniadis
et al., "Economie et Statistiques Avancées" collection,
20 Economica, 1992, France,

Introduction à l'analyse numérique matricielle et à l'optimisation, Masson, 1982, France.

Mathematical methods enabling determination of the positions of center of rotations C and D also enable determination of a certain uncertainty on the result. Especially, a residue indicating whether the considered points really are fixed points appears. If this residue appears to be too large, this means that femur 6 has not been properly immobilized and that point D has moved in the patient's manipulation. To overcome this disadvantage, a marker may be attached to femur 6. As indicated previously, such a marker needs not penetrate into the bone, but can be attached outside of the leg, for example close to the knee against the femoral condyles close to kneecap 10. Thus, for each position of femur 7, the displacement of femur 6, and thus of

point D, can be determined to perform the corresponding correction.

The present invention also provides other means for determining the position of the center of a femur head without requiring driving of a marker into the iliac bone and without requiring immobilization of the pelvis or of the opposite femur 6, or following its motions. In each of the following embodiments, the position of the femur of which the center of rotation is desired to be located is tracked by a marker and triangulation system of the previously described type.

According to a second embodiment of the present invention, motions of the thigh such that the center of rotation of the femur always moves along a trajectory which is clearly distinct from that of the other points of the lower femur end are performed, and the point having a trajectory that maximizes a distance to the trajectory of the marker attached to the lower part of the femur is searched, by an optimization method of the above-mentioned type. The distance between trajectories may take into account "topological" features (for example, and non-limitingly: number of self-intersections in the trajectory, or in the projections of the trajectory on given sub-spaces such as planes or spheres; number of "loops" thus delimited; relative positions of the covered loops while "looking at" the inside or the outside of said loops, inside and outside being understood in the sense of "Ampere's rule", which is conventional in electricity; number and relative positions of points having specific topological features, such as for example stationary points; etc.) or "energetic" features (for example, and non-limitingly: trajectory length; flexion energy of the trajectory, a conventional linear approximation of which is the integral of the square of the second derivative - see Approximation et Optimisation, Pierre-Jean Laurent, Herman 1972; and generally an integral of expressions involving the curve derivatives at orders ranging to the 3rd order or more; etc.). It will be attempted to move the patient's knee so that its lower end describes complex trajectories.

Indeed, the center of rotation will not be able to "follow" these complex motions, and will thus describe a mathematically simpler trajectory, which will enable identifying it. For example, the patient's knee will be moved so that it follows a trajectory including at least one "crossing", an eight for example, or a succession of loops. Then, the trajectories of most femur points will have the shape of an eight or will more generally include one or several crossing points. Only the trajectory of points close to the center of rotation, or even, in certain cases, of the sole center of rotation, will have no crossing point, or less than the trajectory of the reference marker. Thus, even if the center of rotation is not fixed, this center will be able to be identified with respect to point O as being the only point having a trajectory optimizing a distance to the trajectory of the reference marker constructed based on the previously-defined "topological" or "energetic" criteria.

According to a third embodiment of the present invention, not one, but several trajectories such as those corresponding to the second mode are performed. The processing of the data characterizing each of these trajectories is performed according to the second mode, which provides several estimates of the center of rotation. The quality of each of these estimates can be estimated by the value of the used optimization criterion. The point retained as a final estimate of the center of rotation is the result of a statistical processing of this set of estimates, taking into account quality indicators of these estimates (for example, weighted average, non-linear statistical processings, median filtering, etc.).

According to a fourth embodiment of the present invention, motions of the thigh such that its lower part moves according to as "simple" a trajectory as possible, that is, exhibiting none of the topological features used in the second embodiment, and in particular no loops, are performed. The center of rotation of the femur will then be determined as being the femur point having a trajectory minimizing the "energetic" criteria intro-

duced in the description of the second mode. The same optimization methods may be applied. This determination of the center of rotation may however depend on the way in which the thigh rotating motions are transmitted to the iliac bone. Now, this transmission depends on the way in which is urged the thigh, on which compression (force pushing the femur to the pelvis) or traction (force tending to draw the femur away from the pelvis) may simultaneously be exerted for a given stress causing the rotation. To eliminate this effect, motions of the thigh alternating compression and traction may thus be performed.

According to a fifth embodiment of the present invention, not one, but several trajectories such as those corresponding to the fourth mode are followed. The processing of the data characterizing each of these trajectories is performed according to the fourth mode, which provides several estimates of the center of rotation. The quality of each of these estimates can be estimated by the value of the used optimization criterion. The point retained as a final estimate of the center of rotation is the result of a statistical processing of this set of estimates, taking into account quality indicators of these estimates (for example, weighted average, non-linear statistical processings, median filtering, etc.).

According to a sixth embodiment of the present invention, a succession of elementary motions of the thigh are performed. For each of these motions, the position of the femur center of rotation is searched, assuming that it has remained fixed, and a confidence ellipsoid within which the probability of presence of the femur center of rotation is high, for example greater than 95%. Based on several of these confidence ellipsoids, the position of maximum probability of the femur center of rotation is calculated. Each of the confidence ellipsoids is estimated in a referential linked to the femur: possible motions of the femur between the elementary motions are thus allowed for and will not adversely affect the accuracy of the determination of the searched center of rotation. As an example of motions of

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